

Understanding the newly observed $Y(4008)$ by Belle

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(Dated: February 1, 2008)

Very recently a new enhancement around 4.05 GeV was observed by Belle experiment. In this short note, we discuss some possible assignments for this enhancement, i.e. $\psi(3S)$ and $D^*\bar{D}^*$ molecular state. In these two assignments, $Y(4008)$ can decay into $J/\psi\pi^0\pi^0$ with comparable branching ratio with that of $Y(4008) \rightarrow J/\psi\pi^+\pi^-$. Thus one suggests high energy experimentalists to look for $Y(4008)$ in $J/\psi\pi^0\pi^0$ channel. Furthermore one proposes further experiments to search missing channels $D\bar{D}$, $D\bar{D}^* + h.c.$ and especially $\chi_{cJ}\pi^+\pi^-\pi^0$ and $\eta_c\pi^+\pi^-\pi^0$, which will be helpful to distinguish $\psi(3S)$ and $D^*\bar{D}^*$ molecular state assignments for this new enhancement.

PACS numbers: 13.30.Eg 13.75.Lb

Very recently Belle Collaboration observed an enhancement with mass $m = 4008 \pm 40_{-28}^{+114}$ MeV and width $\Gamma = 226 \pm 44 \pm 87$ MeV besides confirming $Y(4260)$ by studying initial state radiation (ISR) process $e^+e^- \rightarrow \gamma_{ISR}J/\psi\pi^+\pi^-$ [1]. Belle experiment also indicated that a fit using two interfering Breit-Wigner shapes describes the data better than one that uses only the $Y(4260)$ [1]. In this work, we named this new structure as $Y(4008)$.

Recently a series of observations of charmonium like states X, Y, Z [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21] is challenging our understanding for non-perturbative QCD. At present how to understand this new structure is one of intriguing and challengeable topics.

In this short note, we are dedicated to the discussion of the possible interpretations for $Y(4008)$.

I. A POSSIBLE CANDIDATE FOR $\psi(3S)$?

In the known charmonium states listed in Particle Data Book, only the mass of $\psi(4040)$ is close to that of $Y(4008)$ [22]. At present $\psi(4040)$ is usually considered as the candidate for $\psi(3S)$. The central value of width of $Y(4008)$ is larger than that of $\psi(4040)$ around 100 MeV. However, due to the large error given by Belle experiment, the mass and width of this new enhancement are consistent with that of $\psi(4040)$.

For $Y(4008)$, Belle experiment also gave $B(J/\psi\pi^+\pi^-) \cdot \Gamma_{e^+e^-} = 5.0 \pm 1.4_{-0.9}^{+6.1}$ eV and $12.4 \pm 2.4_{-1.1}^{+14.8}$ eV corresponding to two solutions in fitting the data [1]. As the candidate of $\psi(3S)$, the decay width of $\psi(4040) \rightarrow e^+e^-$ is 0.86 ± 0.07 keV [22]. Using the above values, we can roughly estimate $B[Y(4008) \rightarrow J/\psi\pi^+\pi^-] = 5.8 \times 10^{-3}$ and 1.4×10^{-2} for the above two solutions if $Y(4008)$

is $\psi(3S)$ state. Due to the large experimental error, the central value of the former one is not contradict the upper limit of the branching ratio of $\psi(4040) \rightarrow J/\psi\pi^+\pi^-$ ($B[\psi(4040) \rightarrow J/\psi\pi^+\pi^-] < 4 \times 10^{-3}$) though the former one is slightly larger than the upper limit of the branching ratio of $\psi(4040) \rightarrow J/\psi\pi^+\pi^-$.

At present, only $Y(4008) \rightarrow J/\psi\pi^+\pi^-$ are reported by Belle [1]. If $Y(4008)$ is $\psi(3S)$, $B[Y(4008) \rightarrow J/\psi\pi^0\pi^0]$ is comparable with $B[Y(4008) \rightarrow J/\psi\pi^+\pi^-]$. Thus $Y(4008)$ can be found in $J/\psi\pi^0\pi^0$ channel.

Although at present the experiments did not give the measurement for $\psi(3S) \rightarrow J/\psi\pi\pi, \psi(2S)\pi\pi$, the transition of $\psi(3S)$ to lower states $\psi(nS)$ ($n < 3$) with two pions being emitted can be solved by the QCD multipole expansion (QCDME) method proposed by Gottfried, Yan and Kuang [23], which is depicted by Fig. 1. In a recent work [24], Ke et al. calculated the transitions

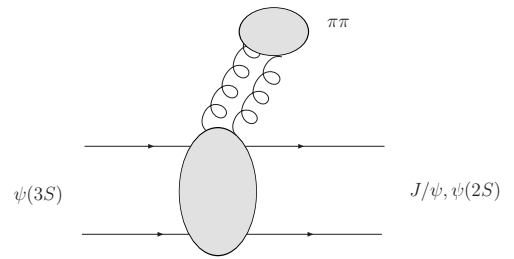


FIG. 1: The transition of $\psi(3S)$ to lower states $\psi(nS)$ ($n < 3$) with two pions being emitted.

of $\psi(3S) \rightarrow \psi(nS)\pi\pi$, and obtain

$$\Gamma[\psi(3S) \rightarrow J/\psi\pi\pi] = 589.91 \text{ keV}, \quad (1)$$

$$\Gamma[\psi(3S) \rightarrow \psi(2S)\pi\pi] = 14.96 \text{ keV}, \quad (2)$$

by adopting the Cornell potential $V(r) = -\frac{\kappa}{r} + br$ [25]

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and

$$\Gamma[\psi(3S) \rightarrow J/\psi\pi\pi] = 12.38 \text{ keV}, \quad (3)$$

$$\Gamma[\psi(3S) \rightarrow \psi(2S)\pi\pi] = 8.84 \text{ keV}, \quad (4)$$

by adopting a modified Cornell potential which includes a spin-related term [26]

$$V(r) = -\frac{\kappa}{r} + br + \frac{8\pi\kappa}{3m_q^2}\delta_\sigma(r)\mathbf{S}_q \cdot \mathbf{S}_{\bar{q}} + V_0,$$

where $\delta_\sigma(r) = (\frac{\sigma}{\sqrt{\pi}})^3 e^{-\sigma^2 r^2}$ and V_0 is the zero-point energy (for more detail, see Ref. [24]). The above numerical results by two potential show that there exists large uncertainty for the estimate of $\psi(3S) \rightarrow J/\psi\pi\pi$ by QCME method, which is indicated in Ref. [24]. However the estimate of $\psi(3S) \rightarrow \psi(2S)\pi\pi$ without spin-related term is consistent with that with spin-related term. If we trust the estimate of $\psi(3S) \rightarrow \psi(2S)\pi\pi$ by QCME method, it is hopeful to search $Y(4008)$ in $\psi(2S)\pi\pi$ channel in future experiments.

Furthermore, if $Y(4008)$ is $\psi(3S)$, we know that $J/\psi\pi^+\pi^-$ is not its main decay channel. $Y(4008)$ can mainly decay into $D\bar{D}$ and $D\bar{D}^* + h.c.$. Due to the fact that $Y(4008)$ is of wide decay width with about 200 MeV, $Y(4008)$ can also decay into $D^*\bar{D}^*$ through its mass tail.

II. A $D^*\bar{D}^*$ MOLECULAR STATE?

There has been a long history about the molecular structure of hadrons. To explain some phenomena which are hard to find natural interpretations in the canonical framework, people have tried to search for new structure beyond it. The molecular structure is one of the possible candidates.

Because the mass of $Y(4008)$ is close to the threshold of $D^*\bar{D}^*$, and $Y(4008)$ is of about 200 MeV wide width, thus $Y(4008)$ can be assumed as a $D^*\bar{D}^*$ molecular state. In the history, Okun and Voloshin studied the interaction between charmed mesons and proposed possibilities of the molecular states involving charmed quarks [27]. Rujula, Geogi and Glashow once suggested $\psi(4040)$ as a $D^*\bar{D}^*$ molecular state [28]. In Ref. [29, 30], Dubynskiy and Voloshin proposed that there exists a possible new resonance at the $D^*\bar{D}^*$ threshold. Because $Y(4008)$ is observed along with $Y(4260)$ which is of $J^{PC} = 1^{--}$, thus the most possible quantum number of $Y(4008)$ is $J^{PC} = 1^{--}$. Furthermore $Y(4008)$ must be a p-wave $D^*\bar{D}^*$. At present one can not use the experimental information to determine the quantum number I^G of $Y(4008)$. Thus $Y(4008)$ can be isosinglet state with $I^G = 0^-$ or isovector state with $I^G = 1^+$. If $Y(4008)$ is a $D^*\bar{D}^*$ molecular state, $Y(4008)$ falls apart into $D^*\bar{D}^*$ by its mass tail, which is depicted in Fig. 2. In the following we will discuss its other possible decay modes.

- (i) $Y(4008)$ as an isoscalar $D^*\bar{D}^*$ molecular state

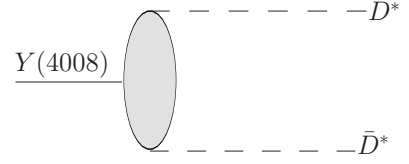


FIG. 2: The diagrams depicting the $Y(4008) \rightarrow D^*\bar{D}^*$ decay.

By the $D^*\bar{D}^*$ recattering effect, $Y(4008)$ with $I^G = 0^-$ can decay into $J/\psi + \eta$, $J/\psi + \sigma$ and $J/\psi + f_0(980)$ by the mechanism depicted in Fig. 3, and into $\chi_{cJ}\omega$ ($J = 0, 1, 2$), $\eta_c\omega$ by Fig. 4. Here J/ψ can be also replaced as $\psi(2S)$ and $\psi(3770)$. By the same mechanism, $Y(4008)$

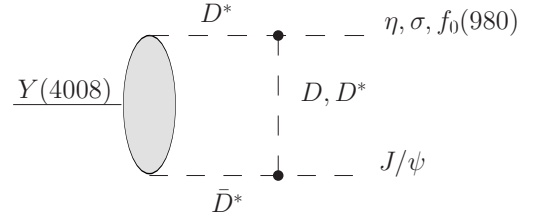


FIG. 3: The diagrams depicting the $Y(4008) \rightarrow J/\psi\eta, J/\psi\sigma, J/\psi f_0(980)$ decays.

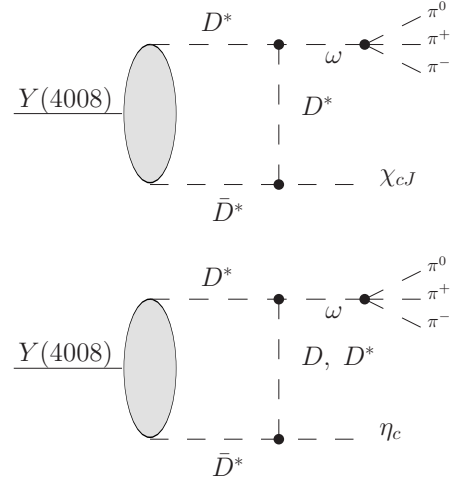


FIG. 4: The diagrams depicting the $Y(4008) \rightarrow \chi_{cJ}\omega, \eta_c\omega$ decays.

also decay into $D\bar{D}$ and $D\bar{D}^* + h.c.$ by exchanging π and ρ mesons between D^* and \bar{D}^* . In fact, as secondary decay, the branching ratio of $Y(4008) \rightarrow D^*\bar{D}^* \rightarrow D\bar{D}, D\bar{D}^* + h.c.$ is comparable with that of $Y(4008) \rightarrow D^*\bar{D}^* \rightarrow J/\psi\eta, J/\psi\omega$.

Because σ and $f_0(980)$ dominantly decay into $\pi\pi$, thus, according to the isospin symmetry, one can roughly esti-

mate

$$\frac{B[Y(4008) \rightarrow J/\psi \pi^0 \pi^0]}{B[Y(4008) \rightarrow J/\psi \pi^+ \pi^-]} \sim \frac{1}{2}. \quad (5)$$

Furthermore the decay mechanism depicted by Fig. 3 can be test in further experiments by analyzing the $\pi\pi$ invariant mass spectrum. If this mechanism is correct, the $\pi\pi$ invariant mass distribution should show the signature of σ or $f_0(980)$.

The branching ratio of $\omega \rightarrow \pi^+ \pi^- \pi^0$ is almost 89.1%, thus ω to $\pi^+ \pi^- \pi^0$ is overwhelming. $\chi_{cJ} \pi^+ \pi^- \pi^0$ and $\eta_c \pi^+ \pi^- \pi^0$ are expected as special and main decay modes of $Y(4008)$. Meanwhile ω also decay into $\pi^+ \pi^-$ and $\pi^0 \gamma$ with the branching ratio $B(\omega \rightarrow \pi^+ \pi^-) = 1.7\%$ and $B(\omega \rightarrow \pi^0 \gamma) = 8.9\%$ respectively [22]. Thus $\chi_{cJ} \pi^+ \pi^-$, $\chi_{cJ} \pi^0 \gamma$, $\eta_c \pi^+ \pi^-$, $\eta_c \pi^0 \gamma$ are important decay modes for $Y(4008)$.

The typical decay modes of $Y(4008)$ with the assignment of $D^* \bar{D}^*$ molecular state ($I^G(J^{PC}) = 0^-(1^{--})$) mainly include $J/\psi \eta$, $J/\psi \pi \pi$, $\chi_{cJ} \pi^+ \pi^- \pi^0$, $\chi_{cJ} \pi^0 \gamma$, $\chi_{cJ} \pi^+ \pi^-$, $\eta_c \pi^+ \pi^- \pi^0$, $\eta_c \pi^0 \gamma$, $\eta_c \pi^+ \pi^-$, $D \bar{D}$, $D \bar{D}^* + h.c.$. As one of the main decay modes, $\chi_{cJ}(\eta_c) \pi^+ \pi^- \pi^0$ should be seen if $Y(4008)$ is a $D^* \bar{D}^*$ molecular state with $I^G = 0^-$. However there exists the difficulty to distinguish $Y(4008) \rightarrow \chi_{cJ}(\eta_c) \pi^0 \gamma$ in the experiment. Here index J of χ_{cJ} can be 0, 1, 2.

(ii) $Y(4008)$ as an isovector $D^* \bar{D}^*$ molecular state

For isovector $D^* \bar{D}^*$ molecular state, $Y(4008)$ can decay into $\pi^0 J/\psi$, $\rho^0 \chi_{cJ}$ ($J = 0, 1, 2$) and $\rho^0 \eta_c$, which are depicted in Fig. 5. The branching ratio of $\rho^0 \rightarrow \pi^+ \pi^-$

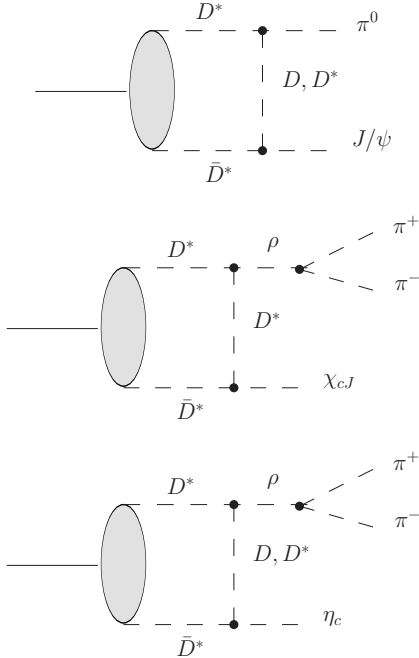


FIG. 5: The diagrams depicting the $Y(4008) \rightarrow \chi_{cJ} \rho, \eta_c \rho$ decays.

is almost 100% [22]. Thus the typical decay modes of $Y(4008)$ as an isovector $D^* \bar{D}^*$ molecular state are $\pi^0 J/\psi$, $\chi_{cJ} \pi^+ \pi^-$ and $\eta_c \pi^+ \pi^-$. Besides these decays, of course $Y(4008)$ can also decay into $D \bar{D}$ and $D \bar{D}^* + h.c.$. Because $J/\psi \pi^+ \pi^-$ is forbidden for an isovector $D^* \bar{D}^*$ molecular state, thus one can exclude the assignment of isovector $D^* \bar{D}^*$ molecular state for $Y(4008)$.

III. BRIEF CONCLUSION

In the above sections, we discuss possible assignments for $Y(4008)$: $\psi(3S)$ and $D^* \bar{D}^*$ molecular state. In these two possible pictures, one finds that the branching ratio of $Y(4008) \rightarrow J/\psi \pi^0 \pi^0$ is comparable with that of $Y(4008) \rightarrow J/\psi \pi^+ \pi^-$. Thus one suggests further experiments to search $Y(4008)$ in $J/\psi \pi^0 \pi^0$ invariant mass distribution.

How to distinguish these two assignments becomes a key problem. In the following we will illustrate the differences of $Y(4008)$ decays for two assignments, which will be helpful to distinguish $\psi(3S)$ and $D^* \bar{D}^*$ molecular state pictures:

(1) Search for $D \bar{D}$, $D \bar{D}^* + h.c.$ decay channels. If $Y(4008)$ is $\psi(3S)$, $D \bar{D}$, $D \bar{D}^* + h.c.$ are main decay channels. If $Y(4008)$ is a $D^* \bar{D}^*$ molecular state, $D \bar{D}$, $D \bar{D}^* + h.c.$, as the secondary decay modes, are comparable with $\chi_{cJ} \pi^+ \pi^- \pi^0$ and $\eta_c \pi^+ \pi^- \pi^0$. Thus one suggests experiments to search these missing decay channels.

(2) Search for $\chi_{cJ} \pi^+ \pi^- \pi^0$ and $\eta_c \pi^+ \pi^- \pi^0$ decay channels. In the picture of $D^* \bar{D}^*$ molecular state, $\chi_{cJ} \pi^+ \pi^- \pi^0$ and $\eta_c \pi^+ \pi^- \pi^0$ are main decay modes. However, as $\psi(3S)$, besides decaying to $D \bar{D}$, $D \bar{D}^* + h.c.$ and $D^* \bar{D}^*$, $Y(4008)$ mainly decays into $J/\psi \pi \pi$. It will be a decisive factor to distinguish $\psi(3S)$ and $D^* \bar{D}^*$ molecular state assignments if the $Y(4008) \rightarrow \chi_{cJ} \pi^+ \pi^- \pi^0, \eta_c \pi^+ \pi^- \pi^0$ can be found in further experiments. One strongly urges our experimental colleague to design more accurate experiments to find $Y(4008) \rightarrow \chi_{cJ} \pi^+ \pi^- \pi^0, \eta_c \pi^+ \pi^- \pi^0$.

Acknowledgments

We thank H.W. Ke for useful communication about their work. We also thank Prof. S.L. Zhu for interesting discussions and useful suggestions. This project was supported by the National Natural Science Foundation of China under Grants 10421503, 10625521 10705001, and the China Postdoctoral Science foundation under Grant No 20060400376.

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